

Split neutrinos - leptogenesis, dark matter and inflation

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We propose a simple framework to split neutrinos with a slight departure from tribimaximal mixing - where two of the neutrinos are Majorana type which provide thermal leptogenesis. The Dirac neutrino with a tiny Yukawa coupling explains primordial inflation and the cosmic microwave background radiation, where the inflaton is the *gauge invariant* flat direction. The observed baryon asymmetry, and the scale of inflation are intimately tied to the observed reactor angle $\sin \theta_{13}$, which can be further constrained by the LHC and the $0\nu\beta\beta$ experiments. The model also provides the lightest right handed sneutrino as a part of the inflaton to be the dark matter candidate.

It is important to connect the origins of inflation, observed neutrino masses, matter-anti-matter/baryon asymmetry, and dark matter within a falsifiable framework of particle physics beyond the Standard Model (SM), which can be constrained by various low energy observations [1]. Since inflation dilutes all matter except the quantum fluctuations which we see in the cosmic microwave background (CMB) radiation, it is important that the inflaton itself cannot be an arbitrary field, its decay must produce the baryons and the dark matter [2].

Furthermore, in order to explain the observed neutrino masses, one must go beyond the SM. In the simplest setting it is possible to augment the SM gauge group by an extra $U(1)_{B-L}$, whose breaking might be responsible for generating the observed neutrino masses. In a supersymmetric (SUSY) setup, this could be realizable within $MSSM \times U(1)_{B-L}$, where (MSSM stands for the minimal supersymmetric SM).

Gauging $U(1)_{B-L}$ in the SUSY context provides a unique D-flat direction which can be the inflaton candidate as studied previously in Refs. [3, 4]. It was pointed out that a small Dirac Yukawa coupling of order $\mathcal{O}(10^{-12})$, can actually help maintaining the flatness of the inflationary potential and provides the right amplitude for the density perturbations, and furthermore - the lightest of the right handed sneutrino (which is now part of the inflaton) can be an excellent dark matter candidate [4].

However, neither inflation nor dark matter requires all the three generations to be Dirac in nature. In fact it is quite plausible that two of the other neutrinos could be Majorana type [5, 6]. Since Dirac neutrino does not carry any lepton number, but the Majorana neutrinos do, it is now an interesting possibility to realize leptogenesis within this simplest setup.

In this paper we will demonstrate that it is possible to split neutrinos with one Dirac and two Majorana types with a non-vanishing reactor angle $\sin \theta_{13}$, which can explain the baryon asymmetry. The overall neutrino masses are now governed by the Dirac Yukawa and the scale at which the $U(1)_{B-L}$ is broken, therefore achieving infla-

tion, dark matter candidate, neutrino masses, and baryon asymmetry with a common setup.

Let us first consider for simplicity a single generation of neutrino with a tiny Dirac Yukawa coupling, h . The superpotential will be given by:

$$W \supset hNH^uL \quad (1)$$

where N , L and H^u are superfields containing the right handed neutrino, left-handed lepton, and the Higgs which give mass to the up-type quarks, respectively. The above superpotential generates a renormalizable potential:

$$V(|\sigma|) = \frac{m_\sigma^2}{2}|\sigma|^2 + \frac{h^2}{12}|\sigma|^4 - \frac{Ah}{6\sqrt{3}}|\sigma|^3. \quad (2)$$

where $m_\sigma^2 = (m_N^2 + m_{L_1}^2 + m_{H_u}^2)/3$ is the soft-SUSY mass and it can be in a wide range, i.e. $m_\sigma \geq \mathcal{O}(500)$ GeV, compatible with the current searches of SUSY particles at the LHC. The A -term is proportional to the inflaton mass m_σ , and the flat direction field σ is

$$\sigma = (\tilde{N} + H^u + \tilde{L}_1)/\sqrt{3}, \quad (3)$$

where \tilde{N} , \tilde{L}_1 , H_u are the scalar components of corresponding superfields. Since the right handed sneutrino \tilde{N} is a singlet under the SM gauge group, its mass receives the smallest contribution from quantum corrections due to SM gauge interactions, and hence it can be set to be the LSP (lightest supersymmetric particle). Therefore the dark matter candidate arises from the right handed sneutrino component of the inflaton.

Inflation happens near the *inflection point* [7, 8], where $A \sim 4m_\sigma$. Near the inflection point it is possible to probe the properties of the inflaton [4]: $\sigma_0 \approx \sqrt{3}m_\sigma/h = 6 \times 10^{12} m_\sigma(0.05 \text{ eV}/m_\nu)$, and $V(\sigma_0) \approx (m_\sigma^4/4h^2) = 3 \times 10^{24} m_\sigma^4(0.05 \text{ eV}/m_\nu)^2$, where m_ν denotes the neutrino mass which is given by $m_\nu = h\langle H_u \rangle$, with $\langle H_u \rangle \equiv v_u \simeq 174 \text{ GeV}$. The largest neutrino mass is $m_\nu \sim \mathcal{O}(1) \text{ eV}$ [9]. The above potential, see Eq. (2), has been studied extensively in order to match the current temperature anisotropy in the CMB radiation. It

is possible to match the central values of the temperature anisotropy denoted by $\delta_H = 1.91 \times 10^{-5}$ and the spectral tilt: $n_s = 0.968$, see [8], for a wide range of masses $100 \text{ GeV} \leq m_\sigma \leq 10^9 \text{ GeV}$ and the Yukawa for the Dirac neutrino in the range: $10^{-12} \leq h \leq 10^{-8}$. The process of reheating and thermalization is quite efficient for a generic flat direction inflaton which radially oscillates around its minimum VEV, $\phi = 0$, and which carries the SM charges, see for details [10]. The temperature at which thermal equilibrium is reached can be estimated to be $T_R \leq 10^6 \text{ GeV}$ for $m_\sigma \sim 1 \text{ TeV}$ in our case.

Scatterings in a thermal bath with the new $U(1)$ gauge interactions also bring the right handed sneutrino into thermal equilibrium. Note that part of the inflaton, *i.e.* its \tilde{N} component see Eq. (3), has never decayed as it is the LSP. Its relic abundance which matches that of the cosmological observations, $\Omega_{CDM} h^2 \sim 0.12$ will be then set by thermal freeze-out, which was calculated in Ref. [4] for a wide range of the lightest sneutrino mass, *i.e.* $100 \text{ GeV} \leq m_{\tilde{N}} \leq 2000 \text{ GeV}$.

Although after inflation the reheat temperature is sufficiently high enough to realize the electroweak baryogenesis within MSSM. However, given the current evidence on the Higgs mass searches at the LHC, it is unlikely that the phase transition would be the first order [11]. Therefore, one would have to rely on other ways of generating the observed matter-anti-matter asymmetry. First of all we would need lepton number carrier, the Dirac neutrinos cannot generate lepton asymmetry.

In our case, the Affleck-Dine baryogenesis would not be realizable even if some of the neutrinos are Majorana. Note that the inflaton is comprised of Eq. (3), where all the three fields take the same VEVs. Once NLH^u takes a large VEV, other directions such as LH^u , LLe , udd can not be lifted at higher VEVs simultaneously. All other directions become massive by virtue of the large inflaton's VEV, see for a review [12]. The *only* plausible scenario would be to realize thermal/non-thermal leptogenesis. However, this would require at least two of the neutrinos to be of Majorana type.

Let us first construct the neutrino masses. It was proposed in Ref. [5] that two right-handed neutrinos, namely N_e and N_τ , could have Majorana mass terms, while the N_μ right handed neutrino has no Majorana mass at the tree-level¹, and it is coupled to the left-handed neutrino which forms a Dirac mass term. Since neutrino has a split nature the authors in Ref. [5] call this scenario schizophrenic. However the Dirac nature is not protected at higher level, so schizophrenic case is equivalent to the quasi-Dirac case [13, 14]. The overall neutrino masses scale is governed by the Dirac Yukawa h . Therefore a

lower limit for $0\nu\beta\beta$ is obtained in both normal and inverse neutrino mass hierarchy. Since the second neutrino Majorana mass can be made zero, the limit for $0\nu\beta\beta$ is about a factor of two larger than the usual Majorana case and this model can be ruled out very soon by next generation of experiments [15].

The model in Ref. [5] is based on S_3 , *i.e.* the permutation group of three objects, see for instance [16]. Note that S_3 has three irreducible representations, **1**, **1'** and **2**, where **1'** is the antisymmetric singlet. The relevant product rules are **1'** \times **1'** = **1**, and **2** \times **2** = **1** + **1'** + **2**. In the basis where the generators of S_3 are reals, the product of two doublets, *i.e.* $a = (a_1, a_2)$ and $b = (b_1, b_2)$ are given by

$$(a_1 b_1 + a_2 b_2)_{\mathbf{1}} + (a_1 b_2 - a_2 b_1)_{\mathbf{1}'} + \begin{pmatrix} a_1 b_2 + a_2 b_1 \\ a_1 b_1 - a_2 b_2 \end{pmatrix}_{\mathbf{2}}. \quad (4)$$

In order to obtain the neutrinos mass matrix, we extend the SM by introducing three right-handed neutrinos: $N_\mu \sim 1$ singlet of S_3 and $N = (N_e, N_\tau) \sim 2$ doublet of S_3 . As in Ref.[5], we assume that the combination L_e , L_μ and L_τ

$$L_2 = \frac{1}{\sqrt{3}}(L_e + L_\mu + L_\tau) \sim \mathbf{1}, \quad (5)$$

transforms as a singlet of S_3 , and that

$$L = \begin{pmatrix} L_1 \\ L_3 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(L_\mu - L_\tau) \\ \frac{1}{\sqrt{6}}(-2L_e + L_\mu + L_\tau) \end{pmatrix} \sim \mathbf{2}, \quad (6)$$

transform as a doublet of S_3 . Equivalently we assume that the right-handed charged leptons combination

$$l_2^c = \frac{1}{\sqrt{3}}(l_e^c + l_\mu^c + l_\tau^c) \sim \mathbf{1}, \quad (7)$$

transforms as a singlet of S_3 , and that

$$l^c = \begin{pmatrix} l_1^c \\ l_3^c \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(l_\mu^c - l_\tau^c) \\ \frac{1}{\sqrt{6}}(-2l_e^c + l_\mu^c + l_\tau^c) \end{pmatrix} \sim \mathbf{2}. \quad (8)$$

We assume two Abelian symmetries $Z_2 \times Z_2'$ under which $L_2 \sim (+, +)$, $L \sim (-, +)$, $l_2^c \sim (+, +)$, $l^c \sim (-, -)$, $N_\mu \sim (+, +)$ and $N \sim (-, +)$. In the scalar sector we assume three sets of $SU_L(2)$ Higgs doublets $H^{u,d}$, $\varphi^{u,d}$ and $\phi^{u,d}$. These three sets are distinguished by means of $Z_2 \times Z_2'$ under which they transform as $H^{u,d} \sim (+, +)$, $\varphi^{u,d} \sim (-, -)$ and $\phi^{u,d} \sim (+, -)$ respectively. The matter content of our model is summarized in table I.

The scalar Higgs doublets $H_i^{u,d} \equiv \{H_1, H_{1'}, H_2\}^{u,d}$ transform as **1**, **1'** and **2** with respect to S_3 where $H_2^{u,d} = (H_a^{u,d}, H_b^{u,d})$. Equivalently the Higgs scalar fields $\phi_i^{u,d} \equiv \{\phi_1^{u,d}, \phi_2^{u,d}\}$ with $\phi_2 = (\phi_a^{u,d}, \phi_b^{u,d})$ and $\varphi^{u,d} = (\varphi_a^{u,d}, \varphi_b^{u,d})$ are doublets of S_3 .

¹ Majorana neutrino mass term $N_\mu N_\mu$ is forbidden by means of an Abelian discrete symmetry.

	L_2	L	l_2^c	l^c	N_μ	N	$H_i^{u,d}$	$\varphi^{u,d}$	$\phi_i^{u,d}$	ξ
S_3	1	2	1	2	1	2	1, 1', 2	2	1, 2	2
Z_2	+	-	+	-	+	-	+	-	+	+
Z_2'	+	+	+	-	+	+	+	-	-	+

TABLE I: Matter content of the model.

The superpotentials are given by

$$W_l = y_1^l L_2 l_2^c H_1^d + y_2^l L_2 (l^c \varphi)_2^d + y_3^l (L l^c)_1 \phi_1^d + y_4^l (L l^c)_2 \phi_2^d, \quad (9)$$

$$W_\nu = h L_2 N_\mu H_1^u + h_s (L N)_1 H_1^u + h_a (L N)_{1'} H_{1'}^u + h_2 (L N)_2 H_2^u.$$

After electroweak symmetry breaking S_3 is completely broken, namely $\langle H_a^{0\alpha} \rangle \neq \langle H_b^{0\alpha} \rangle$, $\langle \phi_a^{0\alpha} \rangle \neq \langle \phi_b^{0\alpha} \rangle$ and $\langle \varphi_a^{0\alpha} \rangle \neq \langle \varphi_b^{0\alpha} \rangle$ where $\alpha = u, d$. Under this assumption it is possible to show that the $M_l \cdot M_l^\dagger$ can be hierarchical and approximatively diagonal, where M_l is the charged lepton mass matrix. So the lepton mixing arises mainly from the neutrino sector. The Dirac neutrino mass matrix is given by

$$m_D = \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} h_s v + h_2 u_b & 0 & 0 \\ 0 & h v & 0 \\ 0 & 0 & h_s v - h_2 u_b \end{pmatrix} + \begin{pmatrix} 0 & 0 & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{6}} \\ -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{6}} \end{pmatrix} \begin{pmatrix} h_a v' + h_2 u_a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -h_a v' + h_2 u_a \end{pmatrix} \quad (10)$$

where $\langle H_1^{u0} \rangle = v$, $\langle H_{1'}^{u0} \rangle = v'$, $\langle H_a^{u0} \rangle = u_a$ and $\langle H_b^{u0} \rangle = u_b$. Note that in the limit $v', u_a \rightarrow 0$ (or $h_a, h_2 \rightarrow 0$) the Dirac neutrino mass matrix is diagonalized on the left by tribimaximal mixing U_{TB} [17]². For values of $h_a, h_2 \neq 0$ we have deviation from tribimaximal mixing. In particular we generate a deviation of the reactor angle from zero in agreement with recent T2K [18] and Double Chooz [19] experiments. Apparently the reactor angle is a free parameter in this model (proportional to h_a, h_2), however we will show below that it is related to the baryon asymmetry.

Let us now consider the right-handed Majorana neutrinos mass terms. We assume a scalar iso-singlet (so coupled only to right-handed neutrino mass terms) $\xi = (\xi_a, \xi_b) \sim 2$ doublet of S_3 . The superpotential is given by

$$W_M = M (N N)_1 + y_\Delta (N N)_2 \xi \quad (11)$$

Since the term $N_\mu N_\mu$ is missing the second neutrino mass state ν_2 does not take a Majorana mass at tree level and gives rise to a quasi Dirac neutrino mass. Such a term can be forbidden by means of Abelian symmetries. For instance, in the Ref. [5], the $N_\mu N_\mu$ term was missing by means of the extra Z_8 symmetry under which $N_\mu \rightarrow \omega^6 N_\mu$ and a new scalar isosinglet $X \rightarrow \omega X$ where $\omega^8 = 1$. Then the Dirac coupling of N_μ is given by $L_2 N_\mu H X^2 / M_P^2$ where M_P is the Planck scale.

We assume $\langle \xi_a \rangle = 0$ and $\langle \xi_b \rangle \neq 0$, then the right-handed neutrino mass M_R is diagonal with masses

$$M_{N_e} = M + \Delta, \quad M_{N_\tau} = M - \Delta, \quad (12)$$

where the two independent free parameters are respectively, M the $U(1)_{B-L}$ breaking scale, i.e. $M \sim 1 - 2$ TeV, and $\Delta = y_\Delta \langle \xi_b \rangle$. In the limit $\Delta \ll M$ the two massive right-handed neutrinos have degenerate masses. It would be now desirable to have a mass splitting between N_e and N_τ , since we would like to create the observed matter-anti-matter asymmetry in the universe.

Light neutrino mass matrix arises from type-I seesaw mechanism [20], $m_\nu = -m_D M_R^{-1} m_D^T$ where m_D is defined in Eq.(10). We assume $u_a = 0$ in Eq.(10) and in order to simplify the notation we observe that the VEVs v, v' and u_b can be reabsorbed with a re-definition of the Yukawa couplings h_s, h_a and h_2 like $h_\alpha \rightarrow v_u h_\alpha / v_\alpha$ where v_u is the standard model Higgs doublet's VEV.

The light-neutrino mass matrix is not diagonal in the tribimaximal basis U_{TB} , and it is given by

$$U_{TB}^T \cdot m_\nu \cdot U_{TB} = \quad (13)$$

$$\begin{pmatrix} \frac{h_a^2}{M_{N_\tau}} + \frac{y_1^2}{M_{N_e}} & 0 & h_a (\frac{y_1}{M_{N_e}} + \frac{y_2^2}{M_{N_\tau}}) \\ 0 & \frac{h}{v_u} & 0 \\ h_a (\frac{y_1}{M_{N_e}} + \frac{y_2^2}{M_{N_\tau}}) & 0 & \frac{h_a^2}{M_{N_e}} + \frac{y_2^2}{M_{N_\tau}} \end{pmatrix} v_u^2$$

where $y_1 = h_2 + h_s$ and $y_2 = h_2 - h_s$. When $h_a = 0$ the above matrix is diagonal. In general the matrix in Eq.(13) is diagonalized by a rotation in the 1 - 3 plane $R_{13}(\theta)$. The lepton mixing matrix is given by $V_l = U_{TB} \cdot R_{13}(\theta)$ and the reactor neutrino mixing angle $(V_l)_{13}$ is given by

$$\sin \theta_{13} = \sqrt{\frac{2}{3}} \sin \theta \approx h_a \sqrt{\frac{2}{3} \frac{(M_{N_e} y_2 + M_{N_\tau} y_1)}{(M_{N_e} y_2^2 - M_{N_\tau} y_1^2)}}. \quad (14)$$

The best fit value [21, 22] of the reactor neutrino mixing angle is about $\sin \theta_{13} \sim \mathcal{O}(0.1)$. For small value of the θ angle, the eigenvalues of the matrix in Eq.(13) are approximatively given by

$$\begin{aligned} m_{\nu 1} &\approx \left(\frac{h_a^2}{M_{N_\tau}} + \frac{y_1^2}{M_{N_e}} \right) v_u^2, & m_{\nu 2} &= h v_u, \\ m_{\nu 3} &\approx \left(\frac{h_a^2}{M_{N_e}} + \frac{y_2^2}{M_{N_\tau}} \right) v_u^2. \end{aligned} \quad (15)$$

² Tribimaximal mixing U_{TB} is given by the first matrix in Eq. (10).

Form this set of equalities we can see immediately that the absolute scale of the neutrinos is fixed by the parameter h that must be about less than 10^{-12} in order to have neutrino mass $\mathcal{O}(0.1)\text{eV}$. Note that from inflation $h \geq 10^{-12}$ for an electroweak scale soft-SUSY breaking masses, therefore predicting large absolute neutrino mass scale in our case. We can obtain y_1 and y_2 from the two neutrinos square mass difference Δm_{atm}^2 and Δm_{sol}^2 , namely

$$\begin{aligned} y_1^2 &= -h_a^2 \frac{M_{N_e}}{M_{N_\tau}} + \frac{M_{N_e}}{v_u^2} \sqrt{h^2 v_u^2 - \Delta m_{sol}^2}, \\ y_2^2 &= -h_a^2 \frac{M_{N_\tau}}{M_{N_e}} - \frac{M_{N_\tau}}{v_u^2} \sqrt{h^2 v_u^2 + \Delta m_{atm}^2 - \Delta m_{sol}^2}. \end{aligned} \quad (16)$$

The parameter h_a is also related to the reactor angle as it is clear from Eq.(14). In particular we can write $\sin \theta_{13}$ as a function of M , Δ , h and h_a .

Let us now estimate the required CP asymmetry for thermal leptogenesis. The asymmetry is calculated by the interference diagrams between tree-level and one-loop diagrams, which give rise to $\epsilon = \sum \epsilon_{\beta\beta}$, [23]

$$\epsilon = \frac{\sum_j \text{Im} [(m_D^\dagger m_D)_{1j}]^2}{8\pi (m_D^\dagger m_D)_{11}} g(x_j) \approx \frac{h_a^2}{2\pi} \frac{M}{\Delta} \sin^2 \alpha \quad (17)$$

where $\epsilon_{\beta\beta}$ is the asymmetry of the decay of the right handed (s)neutrinos into β -family (s)leptons and Higgs, and $x_j = M_j^2/M_1^2$ and we have used the approximation (in the SUSY case) $g(1+z) \approx 2z^{-1}$ and α is the phase of h_a . The baryon asymmetry is given by

$$Y_B = \eta_B/\eta_\gamma \approx (\epsilon \eta)/g_{SM} \quad (18)$$

where $g_{SM} = 118$ and η is the efficiency factor $\eta \sim \text{Min}(1, m^*/m_{\nu_1})$ (see for instance [24]) where m_{ν_1} is the lightest neutrino mass and $m^* = 256\sqrt{g_{SM}}v^2/(3M_P) = 2.3 \cdot 10^3 \text{eV}$. Note that the reheat temperature after inflation is sufficiently high to excite the right handed Majorana (s)neutrinos from a thermal bath.

For fixed values of M , Δ and α , the baryon asymmetry is a function of the coupling h_a . Equivalently, the reactor angle is a function of h_a if we fix h , Δm_{atm}^2 and Δm_{sol}^2 , besides M , Δ and α . In Fig. (1), we show the parametric plot of Y_B versus $s_{13} = \sin \theta_{13}$, varying h_a for different choice of the values of M and Δ by fixing Δm_{sol}^2 , Δm_{atm}^2 at their best fit values, $\alpha = \pi/2$ (maximal CP violation in the lepton sector), and $h = 10^{-12}$ in order to have the neutrino mass scale of about 0.1eV .

To summarize, we have provided a simple realization of split neutrinos where there is one Dirac neutrino whose light Yukawa coupling explains the flatness of the inflaton potential, the amplitude of the CMB perturbations, and governs the overall scale of neutrino masses through $U(1)_{B-L}$ breaking scale. Besides the Dirac neutrino,

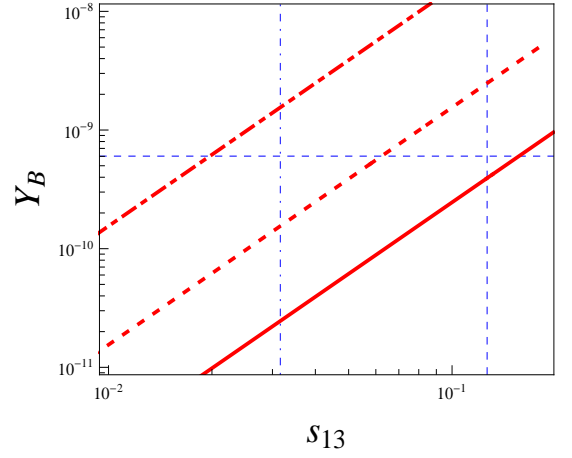


FIG. 1: Dashed with $M = 10^3 \text{GeV}$, $\Delta = 10^{-6} \text{GeV}$, dot-dashed with $M = 10^4 \text{GeV}$, $\Delta = 10^{-5} \text{GeV}$ and continuous with $M = 10^3 \text{GeV}$, $\Delta = 10^{-5.2} \text{GeV}$ fixing $h = 10^{-12}$. The horizontal line is the experimental central value of the baryon asymmetry. The two vertical lines are respectively the 3σ lower bound and the best fit values for $\sin \theta_{13}$ [21].

there are two Majorana neutrinos with a slight departure from tribimaximal mixing, which explains the reactor angle $\sim \theta_{13}$, and tied intimately to the lepton asymmetry obtained from the decay of the two right handed Majorana (s)neutrinos. This could be a minimal model beyond the SM, where we can explain inflation, dark matter, neutrino masses and the baryon asymmetry, which can be further constrained by the searches of SUSY particles at the LHC, the right handed sneutrino, essentially the inflaton component as a dark matter candidate, and from the $0\nu\beta\beta$ experiments.

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